GLobal Ocean ReanalYses and Simulations: GLORYS2V4 product

Scientific and technical notice for users

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Stream 2 version 4 (**GLORYS2V4, 1st January 1993 - 30 December 2015, daily averages**) is produced and is available on request from products@mercator-ocean.fr. GLORYS2V4 global ocean reanalysis product, intended for scientific experts, is presented in this document.

GLORYS2V4 reanalysis relies on three main components:

1. The ocean model (including the surface atmospheric boundary condition and the initial conditions)
2. The data assimilation method
3. The assimilated observations

We review here these three components, changes compared to the previous version (GLORYS2V3) and summary of the validation in the Copernicus CalVal framework.

1. The Ocean Model

- OGCM configuration:

The reanalysis system is based on the version 3.1 of NEMO (Nucleus for European Models of the Ocean) ocean model (Madec, 2008); the configuration uses the tripolar ORCA grid type (1442x1021 grid points) (Madec and Imbard, 1996) at ¼° horizontal resolution (the three poles being located in Antarctica, Northern Asia and Northern Canada). The ¼ ° resolution of the ORCA grid type (ORCA025 hereafter) corresponds to 27 km at the equator, 22 km at Cape Hatteras (Gulf Stream area) and 12 km at high latitudes (Arctic Ocean & regional seas around Antarctica).

The vertical grid has 75 z-levels, with a resolution of 1 meter near the surface, 200 meters in the deepest ocean (> 3000m depth) and 24 levels with the upper 100m.

The bathymetry used in the system is a combination of interpolated ETOPO1 (Amante and Eakins, 2009) and GEBCO8 (Becker et al., 2009) databases. ETOPO datasets are used in regions deeper than 300 m and GEBCO8 is used in regions shallower than 200 m with a linear interpolation in the 200 m – 300 m layer. The minimum depth in the model is set to 12 meters, except in the Bahamas region (~ 3 meters). Three islands have been added in the Torres Strait to diminish the transport and the Palk Strait (between India and Sri Lanka) has been opened with a 3m depth.

A "partial cells" parameterization (Adcroft et al., 1997) is chosen to represent the topographic floor as staircases but making the depth of the bottom cell variable and adjustable to the real depth of the ocean floor (Barnier et al., 2006).

The horizontal pressure gradient is represented by a free surface formulation in which high frequency gravity waves are filtered out (Roullet and Madec, 2000).

The advection of the tracers (temperature and salinity) is computed with a total variance diminishing (TVD) advection scheme (Lévy et al., 2001; Cravatte et al., 2007). A Laplacian lateral isopycnal diffusion on tracers is used ($300 m^2.s^{-1}$ at the Equator and decreasing poleward proportionally to the grid size).

The momentum advection term is computed with the energy and enstrophy conserving scheme proposed by Arakawa and Lamb (1981).

An horizontal bi-harmonic viscosity for the lateral dissipation of momentum (-1×10^{11} m^4 s^{-1} at the Equator and decreasing poleward as the cube of the grid size) is used. In this system, a Laplacian operator (2000 $m^2.s^{-1}$) is applied in the Ob and Ienissei estuaries to avoid local numerical instabilities.

The vertical mixing is parameterized according to a turbulent closure model (order 1.5) adapted by Blanke and Delecluse (1993). Internal-tide driven mixing is parameterized following Koch-Larrouy et al. (2007) for tidal mixing in the Indonesian Seas.

The lateral friction condition is a partial-slip condition with a regionalisation of a no-slip condition (over the Mediterranean Sea).

Instead of being constant, the depth of light extinction is separated in Red-Green-Blue bands depending on the chlorophyll data distribution from mean monthly SeaWIFS climatology.

The reanalysis system uses the thermodynamic-dynamic sea-ice model LIM2 (Fichefet and Maqueda, 1997) with the Elastic-Viscous-Plastic rheology (Hunke and Dukowicz, 1997). The thermodynamics are based on the 2+1 (ice+snow) layers formulation.

- **Surface forcing fields :**

The reanalysis system is driven at the surface by the ERA-Interim reanalysis products (Dee et al., 2011), interpolated onto the ORCA025 grid using the Akima interpolation algorithm. Momentum and heat turbulent surface fluxes are computed from the Large and Yeager (2004) CORE bulk formulae using the following set of atmospheric variables at 3H sampling: surface air temperature and surface humidity at 2 m height, mean sea level pressure and wind at 10 m height. Daily downward longwave and shortwave radiative fluxes and rainfall (solid + liquid) fluxes are also used in the surface heat and freshwater budgets. An analytical formulation (Bernie et al., 2005) is applied to the daily shortwave flux in order to reproduce an ideal diurnal cycle. This parameterization aims at better representing the night-time convection which takes place in the upper most layer of the ocean (Bernie et al., 2007).

Due to large known biases in precipitations and radiative fluxes at the surface, a satellite-based large-scale correction (Garric et al., 2011) is applied to the ERA-Interim fluxes. This correction is applied (1) to the low-passed filtered ERA-Interim fluxes (80% amplitude attenuation at the synoptic scales) in order to avoid any changes on synoptic patterns such as cyclones and (2) to the seasonal climatology in order to avoid any changes of the interannual signal. No corrections are applied at high latitudes (poleward 65°N and 60°S).

Also, specific corrections are applied at high latitudes to counteract knownn warm biases in ERA-Interim surface conditions (Jakobson et al. 2012, Lupkes et al. 2010). In the Arctic Ocean northward of 80°N: surface air temperature is cooled by 2°C and 85% of air humidity is retained. Southward of 60°S in the Southern Ocean: 80% of downward ERAinterim short-wave radiation is retained and 110% of downward ERAinterim long-wave radiation is applied.

Furthermore, in order to avoid artificial drifts of the globally-averaged sea-surface height due to the unbalanced fresh water budget, the evaporation minus precipitation quantities (EmP hereafter) is set equal to zero at each model time-step. In addition, a global mean EmP seasonal cycle is imposed to the one observed by the GRACE geodetic mission.

No global restoring strategy has been implemented in this system to sea surface salinity or to the sea surface temperature. However, a temperature and salinity 3D-restoring towards EN4 products (Good et al., 2013) is applied below 2000m and poleward of 60°S with a representative time scale of 20 years. This latter restoring has been applied to counteract the possible drift of the volume transport in the Antarctic Circumpolar Current.

- **Initial Conditions:**

The simulation started at rest the 4th December 1991, with prescribed temperature and salinity based on EN4 (Good et al., 2013).

Initial conditions for sea ice (ice concentration) were inferred from the NSDIC Bootstrap products for December 1991. The ice thickness has been issued from analytical relationships found between a mean (2002-2009) GLORYS1V1 January sea ice concentration and its ice thickness counterpart. This method allows to considerably reducing the sea ice mass spin up.

- **Time step and ramp up phase:**

The time step is set to 720 sec the first and second weeks of the run; then, the time step is set to 1080s all along the experiment. No data are assimilated during the first two weeks.

2. The Data Assimilation Method

The data are assimilated by means of a reduced-order Kalman filter, based on the SEEK formulation introduced by Pham et al. (1998), with a 3-D multivariate modal decomposition of the forecast error and a 7-day assimilation cycle. Here we present a short description of what we call Système d'Assimilation Mercator version 2 (SAM2).

An important feature of the GLORYS2V4 reanalysis system (implemented also in the real-time global forecasting systems) is that the analysis is performed at the middle of the 7-day assimilation cycle, and not at the end of the assimilation cycle. Doing so, future and past observations are used in the analysis, providing a better estimate of the ocean because the analysis is temporally centred, with respect to the observations used.

The SEEK formulation requires knowledge of the forecast error covariance of the control vector. Altimeter data, in situ temperature and salinity vertical profiles and satellite sea surface temperature are jointly assimilated to estimate the initial conditions for numerical ocean forecasting. Satellite sea ice concentration is assimilated in the system in a monovariate/monodata mode. The forecast error covariance is based on the statistics of a collection of 3D ocean state anomalies (typically a few hundred) and is seasonally variable (i.e. fixed basis, seasonally variable). This approach is similar to the Ensemble optimal interpolation (EnOI) developed by Oke et al., (2008) which is an approximation to the EnKF that uses a stationary ensemble to define background error covariances. In our case, the anomalies are high pass filtered ocean states (Hanning filter, length cut-off frequency = 1/30 days^{-1}) available over the 1993-2009 time period every 3 days. These ocean states come from a reference simulation in which no data assimilation is performed.

A 3D-VAR bias correction method has been implemented to correct large-scale temperature and salinity biases when enough observations are present. The bias correction corrects the slowly varying large scale error of the model whereas SAM2 assimilation scheme corrects the smaller scales of the model forecast error.

These increments are applied with an Incremental Analysis Update (Bloom et al., 1996, Benkiran and Greiner, 2008). The IAU is a low-pass filter, which gives a smooth model integration, without jumps induced at the analysis time when the increment is applied on one time step only (classical model correction). The IAU also reduces spin up effects after the analysis time. In practice, the IAU scheme is more costly than the "classical" model correction because of an additional model integration over the assimilation window.

3. The Assimilated Observations.

The assimilated data consist of satellite SST and SLA data, in situ temperature and salinity profiles, and sea ice concentration. The model innovation (observation minus model equivalent, y-Hx) is computed at appropriate time (FGAT, First Guess at Appropriate Time).

As stated in the model description section, the start time for GLORYS2V4 reanalysis is the 4th December 1991 at 00H UTC. The ocean model is integrated during the first two weeks without data assimilation. Then, all available observations listed below are assimilated.

- **SLA**: provided by CMEMS SLA TAC (CLS: Collecte Localisation Satellites): SEALEVEL-GLO-SLA-L3-REP-OBSERVATIONS-008-001-b product.

Here is a short summary of the Delayed Time altimetric data sets availability:

	Jason-2	Jason-1 new (1)	Jason-1	GFO	Envisat	Envisat new (2)	ERS-1(3) ERS-2
Temporal Time availability: beginning / end	**2008/10**	**2009/02** **2012/03**	**2002/04** **2008/10**	**2000/01** **2008/09**	**2002/10** **2010/10**	**2010/10** **2012/04**	**1992/10** **2002/10**

	Topex new (4)	Topex	Cryosat2	AltiKa	H2-YA2
Temporal Time availability: beginning / end	**2002/09** **2005/10**	**1992/09** **2002/04**	**2011/01**	**2013/03**	**2014/04** **2016/01**

Table: Time period during which altimetric data sets are available

(1) Jason-1 new orbit: starting 2009/02

(2) Envisat new orbit: starting 2010/10

(3) There are no ERS-1 data between December 23, 1993 and April 10, 1994 (ERS-1 phase D – 2nd ice phase)

(4) T/P new orbit: starting 2002/09

The assimilation of SLA observations requires the knowledge of a mean sea surface height. This surface reference, closely linked to the mean circulation / thermodynamical heat and salt content of the ocean, is an adjusted version of Mean Dynamic Topography (MDT hereafter) dataset.

- **SST:** The daily Reynolds 1/4° AVHRR-only daily SST version 2 product (see http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php) is assimilated once at the date of the analysis (i.e. the day 4 at 24H00 of the assimilation cycle).

- **In Situ profiles (T, S):** The CORA data base provided by CMEMS in situ TAC (Coriolis data centre) is assimilated (http://www.coriolis.eu.org/Science/Data-and-Products/CORA-03) in GLORYS2V4.

- **Sea Ice concentration:** The IFREMER/CERSAT products (Ezraty et al., 2007) are assimilated once at the date of the analysis (i.e. the day 4 at 24H00 of the assimilation cycle).

- **Observation error:**

Observation error includes both the instrumental error ($\mathbf{R}_{me}$) and the model representativeness error ($\mathbf{R}_{re}$). These errors are supposed to be uncorrelated and are modelled by diagonal matrices (i.e. the observation errors are mutually uncorrelated).

- **SST**: An empirical error is used. It is function of the representativeness error $\mathbf{R}_{re}$ of in-situ measurements and equal to $\mathbf{R}_{SST}$ = max(0,5°C, $\mathbf{R}_{in\_situ}$(T)).

- **SLA**: The SLA observation error $\mathbf{R_{me}}$ (in variance) is specified according to the knowledge of instrumental features. We use a 2 cm error for JASON (with new orbit or not) and TOPEX-POSEIDON (with new orbit or not) and a 3.5 cm error for ERS-2, GFO and ENVISAT. In October 2010, the Envisat altimeter was brought to a lower orbit, which has led to a slight degradation of data quality (Ollivier and Faugere, 2010). In consequence, a 5.5 cm error is attributed to this altimeter (Envisat new). We use a 4 cm error for Cryosat-2, 2 cm error for Altika and 4 cm error for HY-2A.

- **Mean Dynamic Topography**: A representativeness error for the MDT has been added to the SLA observation error. This error is 5 cm on average. Largest values (~10 cm) are located on shelves, along the coast (model representativeness + observation error due to tides) and in the regions of sharp fronts (Gulf Stream, Kuroshio,...).

- **In situ profiles**: The observation error of temperature and salinity profiles includes both the instrument error and the representativeness error by assuming that the model representativeness is a function of the geographical location and depth. For temperature, this error is dominated by the inaccuracy of the thermocline position given by the model and the data (profilers depth uncertainty can reach 5 m or 2 % of the depth). It ranges from about ~1°C at the surface to 0.1°C below 500m. The higher surface values correspond to mixed layer processes or thermocline motions that are not resolved by the model (filaments, internal gravity waves …). Contrary to the temperature, the salinity observation error can be very large in coastal areas due to run-off uncertainty. The halocline gradient is also weaker than the thermocline gradient, leading to a more homogeneous error on the vertical.

- **Sea Ice concentration:** An empirical error is used. The error is 0.01 when the concentration is equal to 0, then a linear decreasing trend is applied from 0.25 (concentration equal to 0.01) to 0.05 (concentration equal to 1).

4. Changes compared to the previous (GLORYS2V3) system

- New initial conditions for temperature and salinity based on EN4 (Good et al., 2013) are replacing the Levitus (98) climatology used in the previous system. A method using a robust regression model applied to the EN4 monthly objective analysis allowed to re-built the December 1991 water masses conditions. This method considerably reduced the imbalance between a climatology not centred on the initial date and the steric signal seen by the altimetry in 1992.

- The monthly seasonal climatology river runoff is now inferred from Dai et al. (2009). It is a reliable estimate for the world's 925 largest rivers of continental freshwater discharge. This database uses new data, mostly from recent years, streamflow simulated by Community Land Model version 3 to fill the gaps, in all lands areas except Antarctica and Greenland. In addition, the runoff fluxes coming from Greenland and Antarctica ice sheets and glaciers melting has been built from the Altiberg icebergs database project (Tournadre et al., 2012). This complements the estimation of Silva et al. (2006) for Antarctica that was already present in the previous system. The total river runoff represents 1.3 Sv.

- Large-scale corrections of precipitations, resp. radiatives fluxes, at the surface are now performed with the Passive Microwave Water Cycle (PMWC) (Hilburn, 2009), resp GEWEX SRB 3.1 (http: //eosweb.larc.nasa.gov/PRODOCS/srb/table srb.html), satellite data sets.

- A temperature and salinity restoring toward EN4 products (Good et al., 2013) has been added at Gibraltar and Bab-el-Mandeb straits to correctly capture the outflow of Mediterranean and Red seas waters into the Atlantic and Indian oceans.

- The temperature and salinity 3D-restoring applied below 2000m and poleward of 60°S with a representative time scale of 20 years is now made towards the EN4 products.

- Despite the previous corrections and updates, the freshwater budget (EmP) is far from being balanced. In order to avoid any mean sea-surface-height drift due to the poor water budget closure, we add a trend of 1.4 mm/year to the runoffs in order to represent somehow the recent estimation of the global water mass addition to the ocean (from glaciers, land water storage, Greenland & Antarctica ice sheets) (Chambers et al., 2016).

- The sparsity of the observation networks (both altimetry and in situ) during the 7-days assimilation window together with the uncertainties in the MDT estimation are not able to correctly estimate the mean global sea level; we then set to zero the global mean increment of the steric sea surface height.

- A new MDT based on the “CNES-CLS13” MDT with adjustment using high resolution analysis and with improvement on the Post Glacial Rebound (or Glacial Isostatic Adjustment, e.g. Peltier 2004), has been used. This new product also takes into account the last version of the GOCE geoid and is replacing the MDT named “CNES-CLS09” derived from observations (Rio et al., 2011) that was used in the previous system.

- A new 20-year altimeter reference period has been used in place of the previous 7-year reference period for assimilated SLA products.

- The New CORA 4.1 in situ database produced by the CORIOLIS centre (Szekely et al., 2015) is now assimilated (http://www.coriolis.eu.org/Science/Data-and-Products). Compared to the CORAv3.3 release, the CORA4.1 database includes the temperature and salinity vertical profiles from the sea mammals database (33 000 profiles from elephant seals) (Roquet et al., 2011), as well as moorings from TAO/RAMA/PIRATA programs and corrections on XBT measurements. This data set has been extensively quality controlled using classical “in situ” quality control procedures. For years 2014 and 2015, the delayed mode database was not available, so that the real-time database produced by the Coriolis data centre was used instead.

5. Validation

A summary of the validation of GLORYS2V4 based on the **Copernicus CalVal framework [CMEMS-GLO-QUID-001-025-011-017-V3.3.docx)** is given here.

➢ Temperature

- GLORYS2V4 reanalysis has weak biases in temperature with respect to the Levitus 2009 climatology and in situ data (less than 0.4°C on average). Biases of GLORYS2v4 computed from these two datasets are of opposite signs. The largest biases occur in the [50m-100m] layer and in the northern Atlantic and Southern oceans.

- The global mean sea surface temperature (SST hereafter) is close to the observations with a weak (warm) misfit of less than 0.5°C all along the reanalysis. The global positive SST linear trend is highly consistent with AVHRR data. The global mean surface net heat flux is weakly positive (+ 0.5 $W.m^2$).

- Along the equator, temperature profiles are very consistent with observations with RMSE (Root mean square errors) generally smaller than 0.4°C in the water column, apart from the [50m-200m] layers where the RMSE can intermittently reaches 1.2°C in the Indian Ocean. Correlations with equatorial moorings also decrease with depth.

- The heat content constantly increases with time until 2011. Since 2011, the heat content may have stabilised. Only the deeper layers (below 2000m depth) show a constant cooling.

- The thermal structure largely improves with the deployment of Argo buoys (after 2002), mainly in the upper layers (depth < 300m) with a (cold) bias close to 0°C and RMSE against all the in-situ observations less than 1°C. The RMSE also decreases with time in accordance with the observations network density.

➢ Salinity

- The sea surface salinity (SSS hereafter) is generally fresher (less than 0.2 psu) than both the climatology and in situ data sets. However, largest fresh anomalies are found in tropical areas such as the western Atlantic and Pacific oceans. This surface fresh anomaly persists during the whole period covered by the reanalysis. Saltier surface waters are also found in the Arctic Ocean compared to the Levitus climatology. A general salty bias (less than 0.1 psu) is found in the [50m-200m] layer. Both biases and RMSE against all the in-situ observations drastically decrease with time in accordance with the increasing observations network density.

- Positive trends of SSS are seen over most parts of the global ocean. Yet, local negative trends are found in the Arctic Ocean and in the Indonesian Throughflow. This overall positive trend is mitigated by a strong negative trend the first three years of the reanalysis.

- Along the equator, salinity profiles are highly consistent with observations with RMSE generally smaller than 0.2 psu in the water column, apart at the surface where the RMSE is higher and can intermittently reach 0.3 psu °C in the Atlantic Ocean. Correlations with equatorial moorings also decrease with depth with however a generally weaker correlation at the surface compared to sub-surface scores.

- The global salt content shows a weak positive trend with a somehow stabilisation during the last decade. Large interannual variability is found prior the full deployment of the Argo buoys.

➢ Ocean Currents

- GLORYS2V4 reanalysis reproduces well the main ocean currents. However, when compared to the AOML surface drifter climatology, the currents are generally underestimated, especially at mid and high latitudes. It is worth noting that this may be due to an artefact of the AOML surface current climatology as revealed by Grodsky et al. (2011).
- Mean Kinetic Energy (MKE) at 1000m is in good agreement with the ANDRO Argo drift data base all along the boundary currents and the ACC.
- The upper layers equatorial vertical dynamics structures are in well accordance with the moorings observations. The easterly surface current is however stronger in the western Pacific and the core of the Equatorial Under Current (EUC) is weaker. RMSE are generally smaller than 0.25 $m.s^{-1}$ in the water column with a maximum in the lower part of the EUC. Correlations with equatorial moorings also generally decrease with depth.

➢ Sea level

- GLORYS2V4 reanalysis is very close to altimetric observations and has a good ability to describe the sea level variability. Global and regional trends are very well reproduced. The globally averaged RMSE of the analysed sea level is about 6~7cm and the forecast sea level is 0.5cm higher. A global and constant 0.5cm bias is present during the 2002-2006 time period. The GLORYS2V4 reanalysis and tide gauges are in relative agreement except along coastlines where tidal effects are important.

➢ Transports

- Compared to Lumpkins and Speer (2007) estimates, GLORYS2V4 generally overestimates the mean volume transport in all basins and particularly all along the ACC current (by up to 30 Sv), probably due to a sharper N / S gradient of the CNES-CLS013 Mean Dynamic Topography (MDT) in that area. Four GLORYS2V4 transports in the northern Atlantic and Pacific oceans sections are in opposite sign compared to the Lumpkins and Speer (2007) estimates; however, they remain in the Lumpkins and Speer (2007)'s error bars. estimates.
- The Atlantic Meridional Overturning Circulation (AMOC) shows no significant trend throughout the reanalysis period. It is 3 Sv weaker than the RAPID data, but exhibits high correlation (0.86) to these data.
- The Meridional Heat Transport generally is in the error bars of the Ganachaud & Wunsch (2000) and Trenberth & Caron (2001) estimates.

➢ Sea Ice concentration

- Thanks to sea ice concentration assimilation, all the sea ice extent variability (seasonal cycle, interannual variability and trend) is well reproduced in GLORYS2V4. Both sea ice extent and volume show a general decrease (resp. increase) in the Arctic Ocean (resp. around Antarctica).
- Biases and RMSE show a seasonal cycle, with a maximum during summertime, in both hemispheres. Biases are close to zero and RMSE is below 20% in both hemispheres, which is largely in the error bars of the observations.

➢ **Mixed Layer Depth**

- The mixed layer depth (MLD) of the GLORYS2V4 reanalysis exhibits similar patterns with those found in the De Boyer Montegut climatology data. However, GLORYS2V4 strongly overestimates the MLD in North Atlantic Ocean deep convection areas and lightly underestimates the MLD in the Southern Ocean during summertime.

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